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PAIRS OF BUBBLES IN PLANETARY NEBULAE AND CLUSTERS OF GALAXIES

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ABSTRACT

I point to an interesting similarity in the morphology and some non-dimensional quantities between pairs of X-ray-deficient bubbles in clusters of galaxies and pairs of optical-deficient bubbles in planetary nebulae (PNs). This similarity leads me to postulate a similar formation mechanism. This postulate is used to strengthen models for PN shaping by jets (or collimated fast winds: CFW). The presence of dense material in the equatorial plane observed in the two classes of bubbles constrains the jets and CFW activity in PNs to occur while the AGB star still blows its dense wind, or very shortly after. I argue that only a stellar companion can account for such jets and CFW.

Keywords: galaxies: clusters: general — planetary nebulae: general — intergalactic medium — ISM: jets and outflows

1. INTRODUCTION

Chandra X-ray observations of clusters of galaxies reveal the presence of X-ray-deficient bubbles in the inner regions of many clusters, e.g., Hydra A (McNamara et al. 2000), Abell 2052, (Blanton et al. 2001, 2003), A 2597 (McNamara et al. 2001), RBS797 (Schindler et al. 2001), Abell 496 (Dupke & White 2001), and Abell 4059 (Heinz et al. 2002). These bubbles are characterized by low X-ray emissivity implying low density (high quality images of some clusters, e.g., A 2597, Perseus A, and Hydra A, are on the *Chandra* home page: <http://chandra.harvard.edu/photo/category/galaxyclusters.html>). In most cases, the bubbles are sites of strong radio emission. In some cases a pair of radio jets connects the bubble with the active galactic nucleus (e.g., Hydra A: McNamara et al. 2000). The absence

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of evidence of shocks suggests that the bubbles are expanding and moving at subsonic or mildly transonic velocities (Fabian et al. 2000; McNamara et al. 2000; Blanton et al. 2001). The presence of bubbles which do not coincide with strong radio emission (known as ‘ghost bubbles’ or ‘ghost cavities’) located farther from the centers of the clusters in, e.g., Perseus (Fabian et al. 2000), and Abell 2597 (McNamara et al. 2001), suggests that the bubbles rise buoyantly.

The optical morphologies of some planetary nebulae (PNs) reveal pairs of bubbles (cavities), similar in morphology to the pairs of X-ray-deficient bubbles in clusters of galaxies. Examples are the Owl nebula (NGC 3587; PN G148.4+57.0: Guerrero et al. 2003), and Cn 3-1 (VV 171; PN G038.2+12.0; Sahai 2000), which display a pair of low emissivity bubbles along their symmetry axis. Note that in PNs the bubbles are optical-deficient, and not X-ray deficient. In PNs the optical deficient bubbles may actually be filled with X-ray emission, e.g., as in NGC 6543 (Chu et al. 2001). An interesting object is Hu 2-1 (PN G051.4+09.6), which possesses two prominent pairs of bubbles, one pair closer to the center and the other farther out, with inclination between the two symmetry axes (Miranda et al. 2001; the HST images of Cn 3-1 and Hu 2-1 can be found in the list compiled by Terzian & Hajian 2000: <http://ad.usno.navy.mil/pne/gallery.html>). This morphological structure is most similar to the two prominent pairs of X-ray-deficient bubbles in the Perseus cluster (Abell 426: Fabian et al. 2000, 2002). Many other PNs also possess pairs of low emissivity bubbles, although in most cases they are less prominent than the cases quoted above, e.g., NGC 2242 (PN G170.3+15.8: Manchado et al. 1996), and a pair of bubbles within bipolar lobes in M 2-46 (PN G024.8-02.7: Manchado et al. 1996). Some similar bubbles images of PNs and clusters are listed in Table 1.

The morphological similarity between X-ray-deficient bubbles in clusters of galaxies and optical-deficient bubbles in PNs hints at a similar formation process in these vastly different objects. In Section 2 I explore the common and different properties of bubbles in these two classes of objects. The goal is to learn about the formation process of bubbles in PNs from information available from clusters of galaxies. In particular, I argue in Section 3 that the commonly accepted model for the formation of bubble pairs in clusters of galaxies, where the energy is injected in two oppositely propagating jets, strongly hints that the same mechanism operates in PNs. This similarity further constrains the object blowing the jets in PNs to be a compact object, and to blow the jets during the asymptotic giant branch (AGB) phase of the progenitor or during the early post-AGB phase. I argue that the compact object must therefore be a companion. A short summary is in Section 4.

2. COMPARISON OF BUBBLE PROPERTIES

Some properties of bubbles in clusters of galaxies and in PNs are compared in Table 2. The properties of the bubbles are taken from the observational papers cited in the previous section and the theoretical studies cited in the next section. We note that although the general structure in PNs is observed in the optical, inner cavities, not necessarily in pairs of bubbles, may be observed in X-ray (e.g., in the PN NGC 7009; Guerrero, Gruendl, & Chu 2002). Those observations are used to estimate the temperature inside pairs of bubbles used in table 2. The several orders of magnitude difference in some quantities are obvious from table 2. The main qualitative differences between the two classes are: (1) The bubbles in clusters evolve inside the intracluster medium (ICM), which is in hydrostatic equilibrium; if global flow is present, it is highly subsonic. The bubbles in cluster moves outward because of buoyancy. In PNs the bubbles move outward as part of the global outflow of the wind. Gravity is negligible in PNs. (2) In clusters the inflated bubble PdV work goes mainly to push material against the high pressure surroundings, while in PNs the PdV work mainly goes to accelerate AGB wind material to higher velocities.

The relevant similarities between the two types of bubble pairs are as follows. (1) The most relevant similarity is in the morphological structure (see previous section and table 1 for references to high quality images). In particular, in many cases there is a dense region in the equatorial plane between the two bubbles, e.g., the cluster A 2597 (McNamara et al. 2001) and the Owl PN(NGC 3587: Guerrero et al. 2003). (2) In some cases more than one pair of bubbles are seen, e.g., in the Perseus cluster (Fabian et al. 2000, 2002) and in the PN Hu 2-1 (Miranda et al. 2001). (3) In both types of bubbles the density inside the bubble is 2-3 orders of magnitude lower than that in the environment, with an opposite ratio in temperatures. (4) In both cases the typical lifetime of observed bubbles is estimated to be ~ 10 times the estimated duration of the main energy injection phase that forms the bubbles. This value is highly uncertain, and may vary a lot from one system to another. In many PNs the linear increase of outward velocity with distance along the symmetry axis hints that the ejection phase was indeed of short duration compared with the age. (5) In clusters the bubbles are moving subsonically, or mildly supersonically, through the ICM. In PNs the situation is more complicated. Before ionization by the central star or a companion, the sound speed in the AGB wind is $\sim 1 \text{ km s}^{-1}$, while the bubbles expand through the AGB wind at a relative speed of $\sim 10 - 30 \text{ km s}^{-1}$, which is highly supersonic. After ionization, the flow is mildly supersonic or even subsonic. In any case, even during the supersonic phase, the AGB wind is shocked to a temperature much below the bubble's temperature, i.e., the expansion velocity is much below the sound speed inside the bubble. Hence this does not change much the overall characteristic of the bubble flow. Namely, in both types of bubbles the flow speed is much below the sound speed inside the bubble.

3. POSSIBLE IMPLICATIONS OF MORPHOLOGICAL SIMILARITIES

In this section I postulate that the more or less spherical (fat) bubble formation mechanism in clusters of galaxies and in PNs is similar. In clusters there is more information available on the formation mechanism than in PNs. I will use these known and/or well accepted properties of clusters to project on the formation mechanism in PNs.

It is commonly accepted that pairs of bubbles in clusters are formed by axisymmetric energy injection by an AGN, where most of the energy is deposited by two jets at two opposite off-center locations (e.g., Brighenti & Mathews 2002; Brüggen 2003; Brüggen et al. 2002; Fabian et al. 2002; Nulsen et al. 2002; Quilis, Bower, & Balogh 2001; Soker, Blanton, & Sarazin 2002; Omma et al. 2003). An axisymmetrical density structure of the ambient medium is not needed to form the cluster’s bubbles (only very close to the AGN, on a scale much smaller than the bubble size, does the accretion disk influence the flow). This hints, according to the postulate made here, that the bubbles in PNs are also formed by jets. The idea that jets, or collimated fast winds (CFW), shape PNs is not new. Jet shaping was proposed by several authors to explain different morphological features, e.g., jets (or CFW) blown by a stellar companion (Morris 1987; Soker & Rappaport 2000) to explain bipolar PNs, and jets blown at the final AGB phase or early post-AGB phase to form dense blobs along the symmetry axis (Soker 1990; these blobs are termed *ansae*, or FLIERs for fast low ionization emission regions), or shape the PN (Sahai & Trauger 1998). Recently, more quantitative analyses of bubble inflation by jets in PNs were conducted analytically (Soker 2002), and numerically (Chin-Fei & Sahai 2003). However, unlike in clusters, this idea is controversial, with other models suggesting magnetic shaping or axisymmetrical AGB winds (see the debate of Bujarrabal et al. 2000). The latter two processes can work as well, in particular in parallel with jets shaping. Livio (2000) reviews properties of jets in PNs, and compares them with those of other systems known to blow jets. The postulate made here provides insight into the shaping mechanism.

There are other interesting similarities in the bubble morphology between some clusters and some PNs. The density in the jets and the ambient medium decrease with increasing distance from the center. If the jet in a PN is shocked, or shocks the ambient medium, i.e., the AGB wind, close to the center, the dense post-shock regions cool fast, and no bubble is formed. Only when the cooling time of the shocked gas is long a bubble is formed (Soker 2002). In PNs, bubbles are typically expected to be formed by jets quite close to the center, at distances of $z \lesssim 10^{16}$ cm from the center (eqs. 6 and 14 in Soker 2002). The two opposite bubbles expand to all directions, including the center, and when the PN emerges, it is not possible to observe the inner region where the jets expanded without forming a bubble; either this region was destroyed or it is not resolved. However, for slow, speeds of ~ 200 km s⁻¹,

and/or dense jets and winds, the post-shock gas will inflate bubbles only at large distances from the center, $z \sim 10^{17}$ cm (eq. 6 in Soker 2002). The expanding bubbles will not destroy the large inner region, where the jets expand without forming bubbles. This inner region will be observed as a dense region with two low density cones (or cylinders), one in each opposite direction, along which the two opposite collimated jets expanded. According to this flow structure, the bubble will be connected to these cones (or cylinders) at their ends. Such a flow structure is clearly observed in the cluster Hydra A (McNamara et al. 2000), where two well collimated radio jets are abruptly shocked and form radio lobes. The X-ray intensity is high along the borders of the radio lobes. In PNs no such nice jets, as the radio jets in Hydra A, are observed. However, in some PNs the optical morphology is very similar to the X-ray morphology of Hydra A, suggesting a similar flow structure. Again, the PN phase comes long after the jets ceased, unlike in Hydra A where the radio jet is still active, hence the narrow cones through which the jets expanded were broadened by the fast wind blown by the central star, and are difficult, or impossible, to identify. In any case, possible PNs in which the jets inflated bubbles at large distances from the center are M 1-59 (PN G023.9-02.3, image in Manchado et al. 1996), and NGC 7026 (PN G 089.0+00.3; $H\alpha$ image in Balick 1987; see also Terzian & Hajian 2000). In these two PN the inner region is bright, with a faint narrow cylinder along the symmetry axis. The two bubbles in each of these PNs seem to start from the outer boundary of these inner regions, rather than from the center. Yet, another interesting similarity is that the central engine, star(s) in PNs and an AGN in clusters, may not be exactly on the symmetry axis. Examples for the departure of the central engine from the symmetry axis are in the Perseus cluster and the Owl nebula (NGC 3587).

The similarity in several non-dimensional quantities found in the previous section suggests that if the initial flow structure is similar, then the bubble morphologies will be similar, as observed. This leads to the following. (1) The similar shapes strengthens the general idea that jets (or CFW) form and shape the bubbles in PNs, as well as other types of bipolar PNs. (2) The low density in the bubble implies that the jets are fast, with a speed of $> 100 \text{ km s}^{-1}$. Therefore, the object launching the jets must be compact, since the jets speed is of the order of the escape velocity (Livio 2000). (3) The presence of more than one pair of bubbles in the PN Hu 2-1 indicates, as in clusters, multiple episodic events. (4) In clusters the surrounding density increases as radius decreases down to the center. The similar bubble morphologies and the presence of dense material in the equatorial plane between the two bubbles (see previous section) suggests that a similar ambient medium exists in PNs when the jets are blown. Namely, the AGB dense wind is still active, or has ceased only recently, when the jets are blown in PNs. This is possible only if the jets are blown by a companion, or the central star moves extremely rapidly from the AGB to become a compact star that can blow fast

jets. This rapid evolution is in contrast with stellar evolution studies, and is also unlikely to explain the multiple activity (point 3 above; Miranda et al. 2001 argue for a CFW that was blown by a binary system progenitor of Hu 2-1). One of the observational implications is that we should see evidence for fast jets in objects that are still unambiguous AGB stars. A good example is the system OH231.8+4.2 (Rotten Egg nebula), for which Kastner et al. (1998) detect the presence of a Mira inside this bipolar nebula which contains jets (Zijlstra et al. 2001). Zijlstra et al. (2001) present evidence for jets in some OH/IR early post-AGB stars. There are also resolved jets in some AGB stars, e.g., W43A (Imai et al. 2002, 2003) and V Hydrae (Sahai et al. 2003).

The first three points above, of fast jets, or CFW, shaping PNs, sometimes in multiple activity, were mentioned before; see the recent papers by Soker (2002) and Chin-Fei & Sahai (2003) for discussions of the arguments for CFW shaping. The comparison with clusters' bubbles strengthens these points for PNs having pairs of well defined bubbles. Point 4 above, is new. It is unique in strongly hinting at CFW shaping occurring while the primary still blows its AGB wind. This implies that the CFW is blown by a companion.

4. SUMMARY

The purpose of this paper is twofold. Firstly, to point to a similarity in the morphology and some non-dimensional quantities between pairs of bubbles in clusters of galaxies and in PNs (section 2). In the latter group I considered mainly PNs harboring a pair or more of well defined and closed bubbles (i.e., fat bubbles). Examples are given in section 1 and table 1. This similarity is interesting by itself, considering the huge differences in temperatures, size, mass, energy, etc., between the two groups. Secondly, I used this similarity to strengthen models for PN shaping by jets (or collimated fast winds: CFW), and to constraint the formation epoch of the CFW.

Arguments for shaping of PNs by jets and CFW were presented before (references in section 3). Other effects, though, e.g., enhanced equatorial mass loss rate, can also play a role in shaping PNs. It was also assumed that similar mechanisms, e.g., accretion disks, launch jets in AGN, which shape bubbles in clusters, and in PNs (Livio 2000). Here I further postulate similar bubble shaping in cluster of galaxies and in PNs. This allows projection from known properties and processes in clusters to PNs. My main conclusions based on the similarities are as follows (section 3). The similarity in morphology and some properties strongly supports jets or CFW models for the shaping of pair of bubbles in PNs. The ambient medium in PNs, which is the slow AGB wind, need not be axisymmetrical, and may be spherical. The presence of dense material in the equatorial plane constrains the jets

and CFW activity to occur while the AGB star still blows its dense wind, or very shortly after. The requirement that the jets and CFW be fast and the presence of more than one pair of bubbles in, e.g., Hu 2-1, constrains the object that blows the jets and CFW to be a compact companion, i.e., a main sequence or a white dwarf star.

Although I considered here only PNs with well defined pairs of closed bubbles, the results are more general in strengthening the idea that bipolar and extreme elliptical PNs are shaped by jets or CFW blown by an accreting companion.

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A comment to table 1: Free access to images are at these sites:

- [1] http://arxiv.org/PS_cache/astro-ph/pdf/0210/0210054.pdf
- [2] <http://ad.usno.navy.mil/pne/images/rob22.jpg>
- [3] http://arxiv.org/PS_cache/astro-ph/pdf/0007/0007456.pdf
- [4] http://arxiv.org/PS_cache/astro-ph/pdf/0303/0303056.pdf
- [5] http://arxiv.org/PS_cache/astro-ph/pdf/0107/0107221.pdf
- [6] <http://ad.usno.navy.mil/pne/images/vv171.jpg>
- [7] http://arxiv.org/PS_cache/astro-ph/pdf/0010/0010450.pdf
- [8] http://ad.usno.navy.mil/pne/images/he2_104.jpg
- [9] <http://chandra.harvard.edu/photo/cycle1/hcg62/index.html>
- [10a] http://arxiv.org/PS_cache/astro-ph/pdf/0009/0009396.pdf
- also: [10b] http://ad.usno.navy.mil/pne/images/hu21_ha.gif
- [11] http://arxiv.org/PS_cache/astro-ph/pdf/0001/0001402.pdf
- [12] <http://ad.usno.navy.mil/pne/images/ngc6537.jpg>
- [13] http://arxiv.org/PS_cache/astro-ph/ps/0109/0109488.f1.gif
- [14a] <http://ad.usno.navy.mil/pne/images/ngc7009.jpg>
- see also (Goncalves et al. 2003, fig. 1)
- [14b] http://arxiv.org/PS_cache/astro-ph/pdf/0307/0307265.pdf

Table 1. Similar images of PNs and clusters

Structure	Clusters	PNs
Butterfly shape of the bright region; faint along symmetry axis	Abell 478 (Sun et al. 2003, fig 1) [1]	Roberts 22 (Sahai et al. 1999, fig. 1a) [2]
Pairs of fat spherical bubbles near center	Perseus (Fabian et al. 2000) [3]	NGC 3587 (Guerrero et al. 2003, fig. 1) [4]
Closed bubbles connected at the equatorial plane	Abell 2052 (Blanton et al. 2001, fig. 3) [5]	VV 171 (Sahai 2001) [6]
Open bubbles connected at the equatorial plane	M 84 (Finoguenov & Jones 2001, fig 1) [7]	He 2-104 (Sahai & Trauger, 1998) [8]
Pair of bubbles detached from a bright center	HCG 62 (Vrtilek et al. 2002) [9]	Hu 2-1 (Miranda et al. 2001, fig. 2) [10]
point-symmetric elongated lobes	Hydra A (McNamara et al. 2000, fig. 1) [11]	NGC 6537 (Balick 2000, fig. 2) [12]
Pairs of bright bullets along the symmetry axis	Cygnus A (Smith et al. 2002, fig. 1) [13]	NGC 7009 (Balick et al. 1998, fig. 1,4) [14]

Note. — Similr images of bubbles in clusters of galaxies and planetary nebulae (PNs). In clusters these are X-ray images (e.g., with X-ray deficient bubbles), while in PNs they are optical images (e.g., with optical deficient bubbles). In the first five pairs of images the similarity is of high degree. In the last two pairs of images the similarity between the cluster and the PN is of lesser degree.

Table 2. Bubbles and Environment Properties

Property	Clusters	PNs
Environment: type	ICM	AGB wind
Environment: status	hydrostatic	outflow
Observation	X-ray	optical
Size (cm)	$\sim 10^{23}$	$\sim 10^{17} - 10^{18}$
T_{bub} (K)	$> 10^9$	$\sim 10^6 - 10^7$
T_e (K)	$\sim 10^7$	$\sim 10^4$
n_e	$0.1 - 0.01$	$\sim 10^4$
Flow: type	buoyancy	outflow
Flow: speed (km s $^{-1}$)	$\sim 10^3$	$\sim 10 - 30$
τ_{age} (yr)	$\sim 10^7 - 10^8$	$\sim 10^3 - 10^4$
τ_{inj} (yr)	$\sim 10^7$	$\sim 100 - 1000$
E_b (erg)	$\sim 10^{59}$	$\sim 10^{45} - 10^{46}$
\dot{M}_b (M_{\odot} yr $^{-1}$)	< 10	$\sim 10^{-5} - 10^{-6}$
T_{bub}/T_e	$\gtrsim 100$	$\sim 100 - 1000$
V_{flow}/c_s	$\sim 1 - 3$	$\sim 3 - 30$

Note. — The properties of bubbles and their environment in clusters of galaxies and planetary nebulae (PNs). The quantities in the table: ICM: intracluster medium; AGB: asymptotic giant branch; T_{bub} and T_e : temperatures of the gas inside and outside the bubble, respectively; n_e : electron density in the environment of the bubble; c_s : sound speed in the environment; τ_{age} : the typical age of observed bubbles; τ_{inj} : the estimated duration of the energy injection phase to inflate the bubble; \dot{M}_b : the estimated mass injection rate into the bubble during the formation phase. E_b : the energy required to inflate the bubble.